

# Leonardo da Vinci and dental anatomy

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## Abstract

Leonardo da Vinci, the Renaissance polymath, is still recognized today—above all for his oil paintings and mechanical inventions. His anatomical studies have attracted less attention, even though he devoted over 30 years of his life to them. This paper outlines Leonardo's career and research methods and focuses on the importance of his medical images for anatomical research and teaching. Following a short presentation of the state of (dental) medicine in the early Renaissance period, it offers a description of five of his cranial drawings that show the anatomy of the teeth, the nervous and vascular system on inner and outer tables of the skull and the paranasal sinuses in great detail. Leonardo da Vinci had obviously discovered and depicted the maxillary sinus 150 years before the anatomist Nathaniel Highmore, who is usually credited with this discovery. Other anatomical drawings by Leonardo address the correct human dental formula and describe the morphology of the four types of teeth. His handwritten notes show that he recognized the connection between tooth form and function. Finally, this paper evaluates the influence of these discoveries and innovations on the development of dentistry and its establishment as a scientific discipline. There is no doubt that Leonardo da Vinci's preoccupation with the anatomy of the maxillofacial region influenced the development of anatomy and dentistry, even though he never published his anatomical research.

## KEYWORDS

anatomical illustrations, dental anatomy, dental formula, Leonardo da Vinci, paranasal sinuses

## 1 | INTRODUCTION

Leonardo da Vinci (1452–1519) has been considered as one of the most important polymaths of all time. His fame today is mainly based on his paintings. Yet Leonardo was by no means exclusively a painter. He was a sculptor, engineer, architect, natural philosopher, physiologist, and anatomist, among others, and managed to integrate all these disciplines (Sterpetti, 2016). An example of this holistic approach is his attempt to explore the analogy between the human microcosm and the world's macrocosm (Vollmuth, 2004).

Leonardo embarked on none of his scientific endeavors for their own sake. They all influenced and inspired each other. His lesser-known activities include his anatomical oeuvre. He had a genuine

and well-motivated interest in studying the anatomy, and later also the physiology, of humans and animals. This lifelong interest resulted in many notebooks filled with countless sketches and rather sparse notes, which were a challenge for his contemporaries to interpret as they were so far ahead of their time (Sterpetti, 2016).

Leonardo did not explicitly explore dentistry as such. Dentistry was not yet perceived as an independent scientific discipline during the artist's lifetime, the Renaissance period. However, he was very much interested in the anatomy and morphology of the cranium and rediscovered a number of anatomical structures (O'Malley & Saunders, 2003).

The medical knowledge of the ancient world was forgotten after the fall of the Roman Empire. The late Middle Ages saw the

beginnings of a period of transformation in numerous areas and a return to the values of antiquity. Science and the arts began to exert an unprecedented influence on medicine (Gombrich, 1996). Based on Greek and Latin sources, the medical knowledge of antiquity was revised and edited in terms of its reception history (Nutton, 2013). Initially, the scientific, especially the medical insights of the time were still influenced by the ancient authors, but their claims could now be verified or falsified, e.g. by autopsies (Vollmuth, 2004).

Leonardo da Vinci played a prominent role in this endeavor. His anatomical illustrations were the first to record the macroscopic anatomy of the human body, precisely and in minute detail, including detailed representations of the cranium, teeth, and sinuses (Keele, 1979). Leonardo was the first to correctly identify and document the human dental formula. He also described the shape of the different types of teeth and the relationship between their shape and function as well as describing the muscles in the craniofacial region (Gerrits & Veening, 2013).

## 2 | HISTORICAL CONTEXT: RECEIVED KNOWLEDGE BEFORE THE RENAISSANCE PERIOD

To appreciate the innovative nature of Leonardo's drawings, we must first assess the state of knowledge as it existed at the beginning of the Renaissance period. Dentistry did not exist as a separate field until the 18th century (Groß, 2019; Hoffmann-Axthelm, 1981), but (para)medical practitioners dedicating themselves to dental treatment existed in historical cultures at least since antiquity. They had, however, little actual knowledge of dental anatomy and pathology. Toothaches were treated with various medicinal mixtures or, alternatively, by extraction. There are examples of teeth from prehistoric or historic times restored with different filling materials, but these are very rare (Alt, 1993; Nicklisch et al., 2019). Little was known about the development of dental diseases. The most widespread explanation for caries was probably that of a "tooth worm" attacking the mouth and teeth (Hoffmann-Axthelm, 1981).

Greek sources already describe a numbering system for individual teeth and descriptions of the root and crown anatomy of molars. In addition, based on their size and shape, the anterior teeth (*dentes pares, anteriores*) were differentiated from the posterior teeth (*dentes maxillares, dentes quadrupli*) (Hoffmann-Axthelm, 1981). Until the Middle Ages, the scale of the adult dentition was still uncertain; some authors stated that women had 30 teeth while men had 32.

From the 12th century onwards, however, also with reference to Galenus of Pergamon, the Roman physician and anatomist, there was agreement: the complete adult dentition comprises 32 teeth (Hoffmann-Axthelm, 1981). In addition, the ancient Greeks already distinguished between deciduous and permanent teeth, describing the phase between ages 5 and 13 as the mixed-dentition phase (Hoffmann-Axthelm, 1981). Thus, at the beginning of the Renaissance period, the number of teeth in a complete dentition and

the two types of dentitions were known. In addition, a distinction was made between anterior and posterior teeth, as defined by different external features.

As the epoch progressed, popular interest in anatomy increased, with teeth coming more and more into focus (Lässig & Müller, 1985). However, the large number of different surviving surgical instruments still testifies to extraction as the most common treatment. There are also records of pain treatments in which the pulp was opened by means of a drill and devitalized by cauterizing. We also have evidence, from the 14th century onward, that carious spots were filed off and fillings made of various metals were placed (Hoffmann-Axthelm, 1981; Papadiochos et al., 2017). The cariogenic properties of sugar were also recognized, as was the fact that the consumption of abrasive food leads to the destruction of teeth by abrasion (Groß, 2019).

The rise of the sciences during the Renaissance period thus also had an impact on dentistry. The work of Leonardo da Vinci, however, stood at the beginning of this development, well before *De humani corporis fabrica* by Andreas Vesalius (Vesalius, 1970) revolutionized anatomy (Underwood & Singer, 1962) and the first purely dental treatise was published with Bartolomeo Eustachi's *Libellus de dentibus* (Eustachi, 1951; Groß, 2019; Shklar & Chernin, 2000). The influence of Leonardo's anatomical studies is, however, not limited to (dental) medicine and the establishment of the natural sciences in the Renaissance, but undoubtedly also has a parallel effect on the implementation of anatomical knowledge and principles in art (Knox, 1852).

## 3 | STATIONS OF LEONARDO'S LIFE: CONNECTION OF ART AND ANATOMY

Leonardo da Vinci was born in Vinci near Florence, Italy on April 15, 1452. Coincidentally, the beginnings of the Italian Renaissance can also be dated to the middle of the 15th century and located in Florence, from where it spread to the other Italian city-states (Gombrich, 1996). Young Leonardo, an out-of-wedlock son of Ser Piero Fruosino di Antonio da Vinci, a wealthy Florentine legal notary, received schooling from his uncle and from a priest (Sterpetti, 2016). He then took up an apprenticeship with the well-known painter Andrea del Verrocchio in the painter's "bottega" between 1464 and 1470 (O'Malley & Saunders, 2003). "Bottegas" were painters' workshops. They existed in all major cities and taught a broad range of subjects, including architecture, engineering, and mathematics.

In addition, a basic knowledge of anatomy was part of a painter's training to allow them to reproduce skin and muscle structures as authentically as possible. It was common for artists to carry out anatomical studies and even to obtain permission to perform sections on corpses (Sterpetti, 2016).

Antonio del Pollaiuolo is considered the first artist to examine the human body in more detail (Vollmuth, 2004). He was followed by Michelangelo Buonarroti, Raffaello Santi, and Albrecht Dürer, to

name just a few (Underwood & Singer, 1962). Leonardo was therefore by no means the only artist of the time whose interest in the human body and its systems was aroused by anatomy and who subsequently engaged in anatomical studies. However, he stands out from this group of artists in that he was not content to depict humans from the outside. On the contrary, he was always keen to find out how everything was connected—in other words, to grasp the concept of the human body in its entirety, in the interplay of its individual parts, both inside and out.

Leonardo was an artist who wanted to understand the entire world, down to the most minute detail. To accomplish this ideal, he increasingly carried out his own experiments instead of referring to explanations in textbooks. These experiments are the foundation of his wide-ranging interests and explain his affinity for research in almost every scientific discipline (Gombrich, 1996).

After completing his training with Verrocchio, Leonardo continued to work for the artist and took on his own commissions as a painter and sculptor in Florence. In 1482, at the age of 30, he offered his services to Ludovico Sforza, Duke of Milan, but not as a painter—rather, he hoped to be employed as an engineer to develop military technology. Although he was not accepted for the position, he moved to Milan and took on additional commissions. From his notebooks, it is clear that he still pursued everything that interested him: he continued to develop war machines, while at the same time he was engaged in the theory of proportion, anatomy, and physiology (Zöllner, 1999). The result that is most famous today is probably his solution of the enigma of the Vitruvian Man, which he accomplished around 1492 (Fehrenbach, 2011).

Between 1487 and 1490, Leonardo worked on the construction of the crossing tower (tiburio) of Milan Cathedral (Bott, 1984). As his notes show, he was concurrently studying the anatomy of the human cranium and creating precise cranial drawings. Marielene Putscher presumes that the two are closely related and hypothesizes that Leonardo researched the structure of the human cranium to gain inspiration for the construction of the cathedral's dome (Vollmuth, 2004).

Throughout his life, Leonardo repeatedly developed such synergisms. As a scientist of the Renaissance, he was fascinated by the human brain, more precisely by the process of vision and the ventricles of the brain that are associated with it and that had already been described by Galenus. In Leonardo's initial sketches, we clearly recognize the Aristotelian concept of cerebral vesicles, which Galenus had also referred to. The cerebral vesicles are directly related to the *senso comune* and vision. It was assumed that the optical stimuli are conducted via the optic nerve into the first vesicle, *impressiva*, where the stimuli are processed as a “first impression” and continue on to the *senso comune* just mentioned. Here the stimuli are evaluated, with those that are considered important being passed on to the *memoria*, where they are remembered (Zöllner, 2009). The *senso comune* is attributed the greatest importance and Leonardo assumed that it was the seat of the human soul (Keele, 1979).

Looking at drawings made 15 years later, we find fairly accurately depicted brain ventricles (see RL 12602r). How did Leonardo manage to improve on the underlying concept? By once again combining his many skills. As in bronze casting, he injected wax into the preparation of a male bovine brain and was able to recognize the actual shape from the wax casts. This procedure was unique in the Renaissance period; it was not repeated until the 17th and 18th centuries (Huard, 1967).

There are numerous other examples of Leonardo's creativity in experimentation, ranging from inflating a goose lung to exploring reflexes using a frog's spine (Jose, 2001).

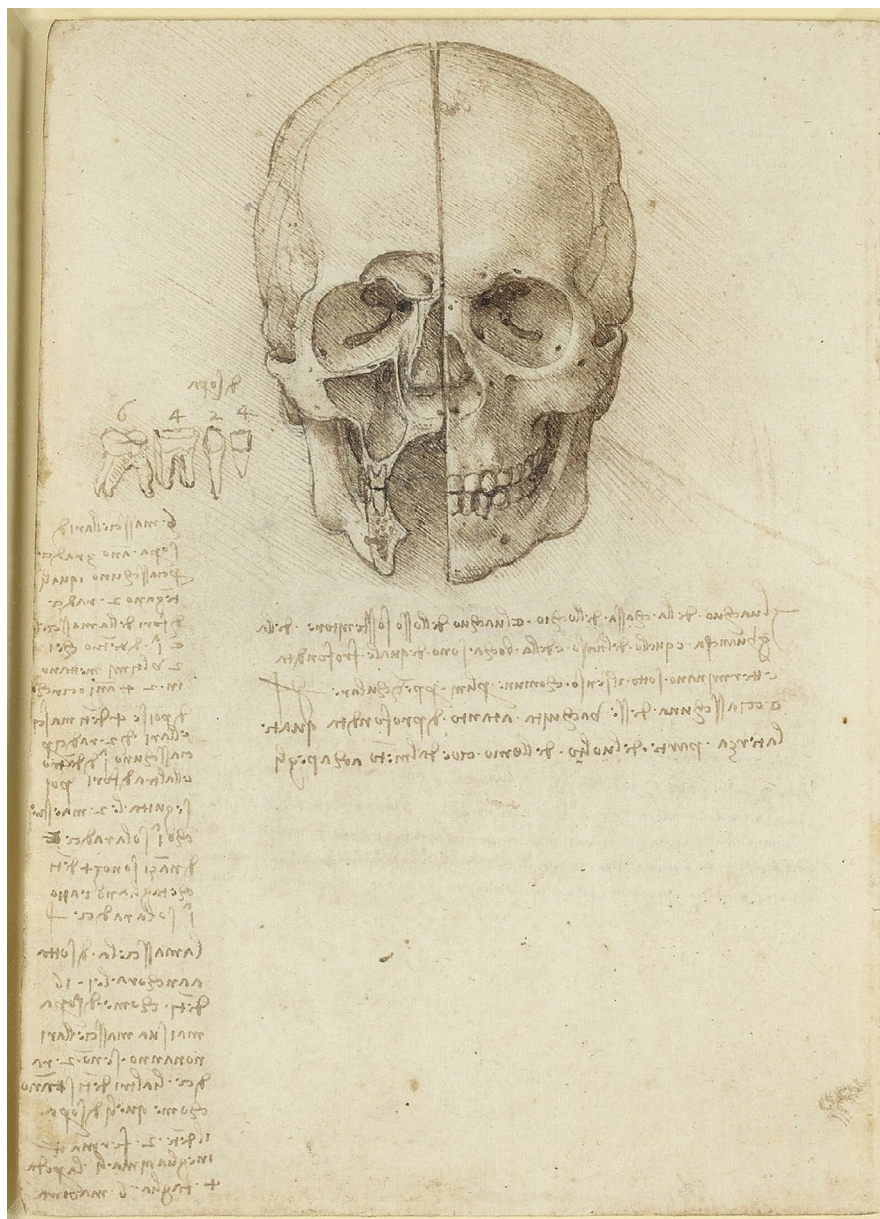
In fact, sections were an important part of Leonardo's research. He initially participated in public sections (Braunfels-Esche, 1961), anatomizing various organs or body parts himself (Heichele, 2016), and, by his own count, personally dissected 30 corpses in his lifetime (Tubbs et al., 2018). He recorded his thoughts and findings in the form of sketches, most of them with brief textual explanations. Yet each drawing also stands on its own and does not require explanation by the supplementary text. In his drawings, Leonardo was able to depict any given structure and even to illustrate movement (Putscher, 1984).

For Leonardo, as a trained artist, drawing was a way of processing and recording information. He used this technique not only for sections, but also when reading anatomical textbooks, which were his main sources of information during his first phase of anatomical studies, converting what he had read into sketches for better understanding (Herrlinger, 1967, 1981). The process of drawing therefore aided him in acquiring knowledge (Putscher, 1984).

Anatomical facts were traditionally recorded by written description, but for Leonardo this was not an option. For him, the art of drawing constituted a universal language. Being an *uomo senza lettere*, someone who had not mastered the scientific language, Latin, drawings were the ideal means to record and reproduce knowledge (Huard, 1967). Pictorial representations—images—were an ancient and proven means of passing on content to a broader public. Church windows or reliefs are vivid examples of this, as they make the teachings of Bible transparent to every onlooker—whether educated nobleman or a poor peasant (“the poor man's Bible”) (Brocket, 2019; Brown, 1990).

Societies are united by a common fund of knowledge. It is obvious that Leonardo, the “uneducated universal genius”, wanted to make his discoveries accessible to all interested parties, regardless of their proficiency in Latin. But Putscher's interpretation goes further than that. She suggests that the drawings were not intended to illustrate the text, but that they were themselves in focus, with text inserted only where images as sole vehicles of information were pushing their limits (Putscher, 1984). Leonardo himself held that illustrations were ideally suited for imparting anatomical knowledge, since it is much more complicated to translate detailed structures into words and words back into understanding than to reproduce them in a proficient drawing (Jose, 2001).

Leonardo lived and worked in Florence, Milan, and Rome. In 1516–17, he finally heeded the request by Francis I, King of France, and moved to that country. There, in the Château du Clos Lucé at



**FIGURE 1** RCIN 919058v Leonardo da Vinci, The skull sectioned, 1489, traces of black chalk, pen and ink, 183 × 130 mm, Windsor Castle, Royal Library. Royal Collection Trust/© Her Majesty Queen Elizabeth II 2021. The center of the upper half of the sheet shows a frontal view of a sagittally hemisected cranium. The left half shows the bony surface, including the maxilla and mandible in full in occlusion. The right half of the cranium is opened in the frontal plane, providing a view of the frontal sinus, maxillary sinus, an occluding pair of premolars, and the mental foramen. To the left of the cranium, there are drawings of the four types of maxillary teeth and an indication of the correct number of teeth in the upper and lower jaws. The lower half of the sheet is taken up by explanations of the individual tooth types

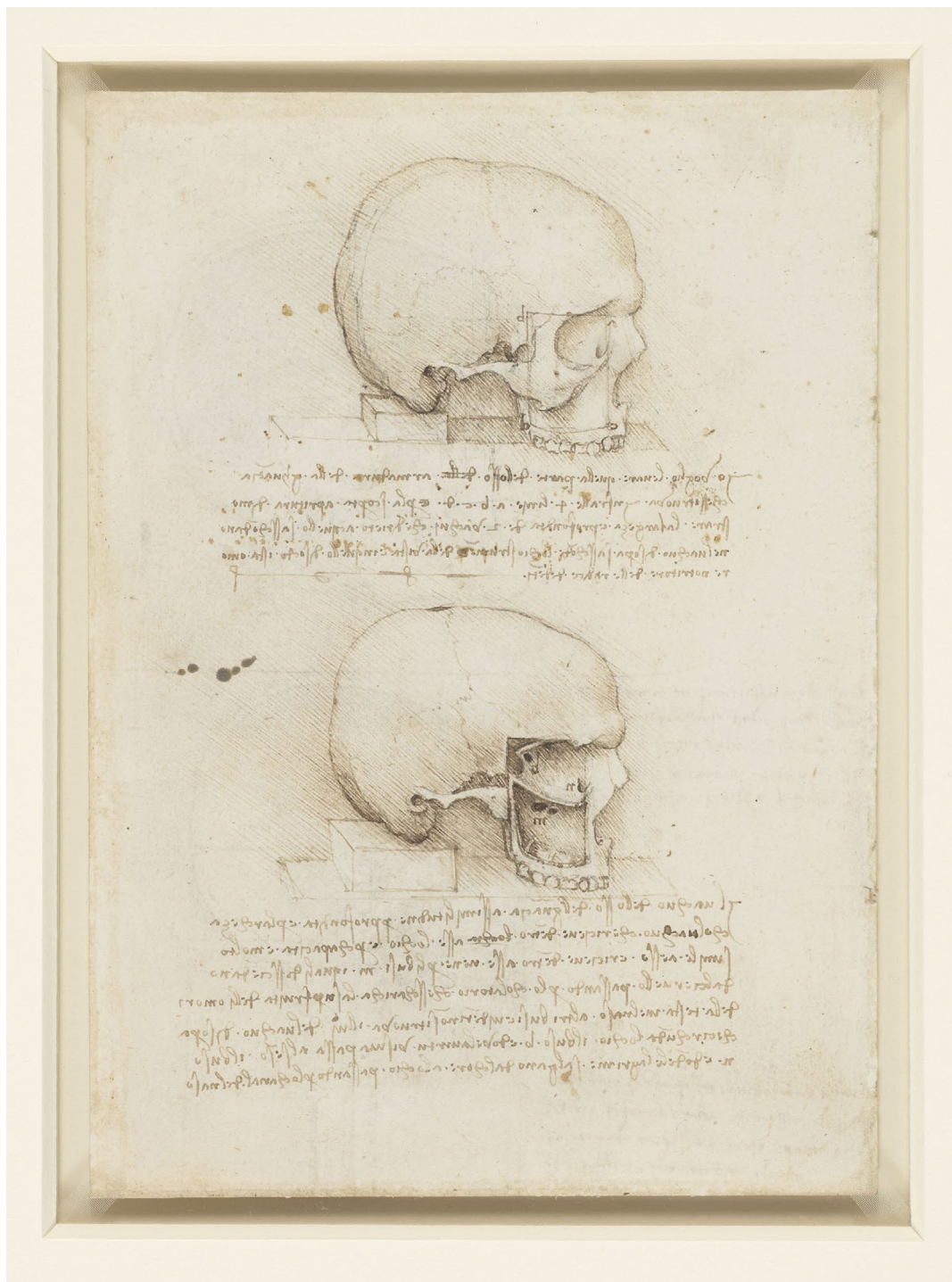
Ambois, he spent the last years of his life, researching and working until his death on May 2, 1519 (Bott, 1984).

#### 4 | LEONARDO DA VINCI AND DENTISTRY

Leonardo da Vinci was a polymath who studied many aspects of life. Nonetheless, he was not a physician, and the role of medicine prior to that time had mainly been to prescribe commonly traded prescriptions.

Leonardo was certainly not a follower of these traditional—read “primitive”—approaches to medicine. On the contrary, it was precisely this type of medicine, practiced uninterruptedly for thousands of years, that the scientific mind finally began to overcome in Renaissance times. Thus, Leonardo, as an anatomical and physiological researcher, was deeply interested in the medical aspects of his discoveries. Based on his sections, he was, for example, the first to discover and recognize atherosclerosis as a cause of death (Keele, 1979).

Aesthetics were immensely important in the Renaissance, and teeth played a central role in this. The concept is illustrated by the



**FIGURE 2** RCIN 919057v Leonardo da Vinci, The cranium, 1489, traces of black chalk, pen and ink, 188 × 134 mm, Windsor Castle, Royal Library. Royal Collection Trust/© Her Majesty Queen Elizabeth II 2021. Two right-facing crania without mandibles are arranged one above the other, both supported for parallel alignment in the area of the mastoid process. Handwritten notes are present below each cranium. The upper cranium shows the bony surface and auxiliary lines that indicate how the lower cranium is opened. In the lower cranium, the inner walls of the orbita and the maxillary sinus are visible through a fenestration. In the maxillary sinus, the ostium is visible medially, in addition to three bony septa on the sinus floor

following: Leonardo tried to make ideal ugliness tangible as an antipode to the attempt to define ideal beauty. His studies, for example, included sketches of faces with collapsed mouths due to edentulism and lack of prosthetic treatment. Conversely, we may deduce that healthy teeth

are part of the ideal image of beauty (Baur, 1984). Yet Leonardo drew attention to teeth not only in his caricatures of beauty and ugliness.

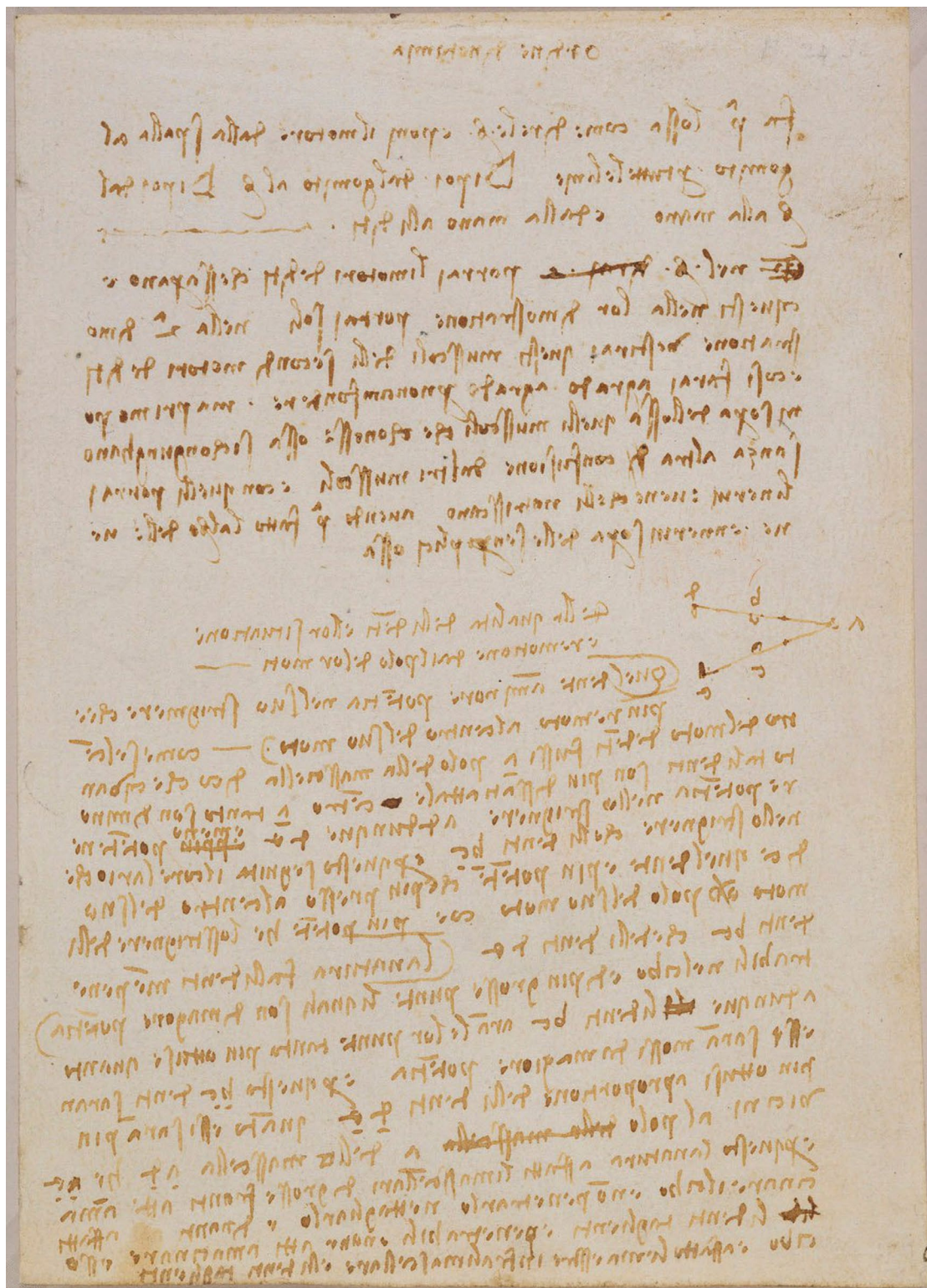
We have some information about Leonardo's anatomical approaches, but few authors have directly examined Leonardo's art from



**FIGURE 3** RCIN 919057r Leonardo da Vinci, The skull sectioned, 1489, traces of black chalk, pen and ink, 188 × 134 mm, Windsor Castle, Royal Library. Royal Collection Trust/© Her Majesty Queen Elizabeth II 2021. Two left-facing crania are depicted one above the other on the right side of the sheet; the left half shows handwritten notes. Both crania are complete with mandibles and segments of the spine. The calvaria of the upper cranium is opened sagittally and transversely. Maxillary and mandibular incisors, premolars, and molars are shown in edge-to-edge anterior occlusion. The lower cranium is completely hemisected sagittally, exposing the interior of the calvaria, the frontal sinus, and the nasal cavity, in addition to the incisal canal and the mandibular foramen

a “dental perspective” or with an emphasis on teeth. This was understandable enough at a time when dentistry was not yet established as an independent discipline. But which aspects of Leonardo's work

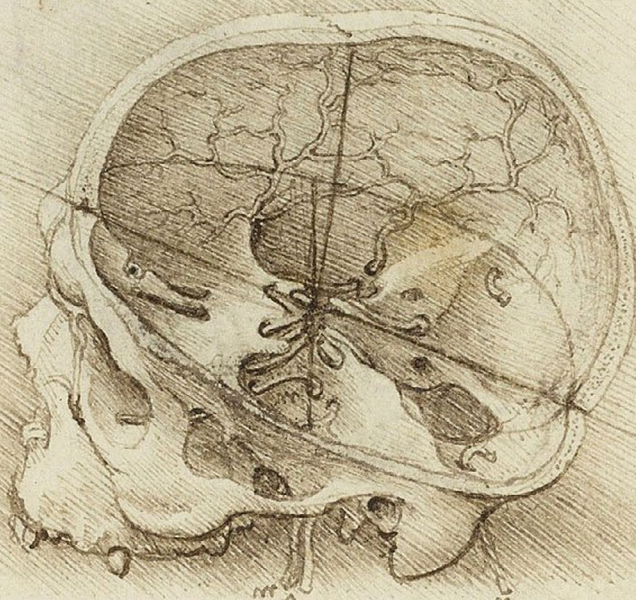
would fall under the heading “of dental relevance”? Since the artist himself did not distinguish between the individual disciplines, the topic must be assessed artificially and in retrospect. The focus of the



**FIGURE 4** RCIN 919041 Leonardo da Vinci, Notes on the treatise on anatomy, and the teeth, 1508, pen and ink, 193 × 138 mm, Windsor Castle, Royal Library. Royal Collection Trust/© Her Majesty Queen Elizabeth II 2021. Handwritten notes documenting Leonardo's thoughts regarding the form, function, and chewing force of human teeth. To illustrate the center of the masticatory forces at their greatest, a small sketch appears about halfway down the right. On it, four dots symbolize different types of teeth; the intersection of the two axes indicates the center of motion, i.e., the temporomandibular joint

following descriptions will therefore be on his cranial sketches, because this is where the anatomical structures relevant to dentistry are

found and because they represent Leonardo's most revealing drawings and thoughts concerning the teeth.



*[A large, dense page of handwritten text in a cursive script, likely from a manuscript.]*

**FIGURE 5** RCIN 919058r Leonardo da Vinci, The cranium sectioned, 1489, Pen and ink, 190 x 137 mm, Windsor Castle, Royal Library. Royal Collection Trust/© Her Majesty Queen Elizabeth II 2021. The top half of the sheet shows a left-facing calvaria opened both sagittally and transversely just above the base of the skull. The wide view illustrates the vascular and nervous systems inside the calvaria and on the base. The insides of the os frontale and os parietale are dominated by vascular impressions and ramifications, while entry or exit points of vessels are marked on the bones (a and m). The nasal region of the viscerocranium shows the vena angularis and v. dorsalis connected to the vena frontalis (supratrochlear). The maxilla is clearly of no great importance in the drawing, only showing some incisors and a premolar alongside empty alveoli. The lower part of the sheet holds eight lines of text in which Leonardo describes the position of the senso commune, which he assumes at the intersection of the two lines crossing the skull above the hypophyseal fossa. In addition, he comments on the blood supply via the depicted vessels

All the sketches mentioned below are in the Royal Library in Windsor Castle. These are the sheets numbered RCIN 919058v (Figure 1), RCIN 919057v (Figure 2), RCIN 919057r (Figure 3), RCIN 919058r (Figure 5), and RCIN 919059r (Figure 6), all created in 1489 A.D. These five sketches, together with a handwritten page dating to 1508 (RCIN 919041, Figure 4) from Leonardo's notes, form the basis for the following presentation. Broad access to Leonardo's extensive anatomical oeuvre is provided by the description of the original anatomical drawings in *Leonardo da Vinci: Anatomical drawings from the Royal Library, Windsor Castle* (Keele and Roberts, 1984, 2013). A seemingly promising publication entitled *Leonardo da Vinci: The complete works* (Da Vinci, 2006) has been criticized because of its unwieldy format (13 x 15 cm). The most important recent publication *Leonardo da Vinci: A life in drawing* has appeared on the 500<sup>th</sup> anniversary of Leonardo's death in 2019 (Clayton, 2019).

#### 4.1 | The maxillary sinus and surrounding anatomical structures

Two of the five drawings discussed (RCIN 919058v, RCIN 919057v) depict the maxillary sinus (Figures 1 and 2). This would not seem surprising from today's point of view—except that the maxillary sinuses had never been described previously (15th century). They are usually assumed to only have been discovered 150 years later, when Nathaniel Highmore was the first to describe what was popularly referred to as the *antrum Highmori* (Mavrodi & Paraskevas, 2013). We cannot entirely dismiss the idea that Galenus or other ancient anatomists knew about this structure in the maxillary bone, but we have no pertinent description or representation (Mavrodi & Paraskevas, 2013).

Sheet RCIN 919058v (Figure 1) from 1489 shows a frontal view of a human cranium in the top center, four schematic illustrations of the tooth types to the left, and written annotations in the lower half. The cranium is hemisected vertically, showing two views: the side of the cranium perceived by the observer on the right reflects the outer surfaces of the bony facial structures, whereas the left side is cut open frontally. The incision through the visceral cranium reveals structures such as the maxillary and frontal sinuses mentioned above. At the same time, a two-rooted premolar in the maxilla and its antagonist in the mandible are segmented, showing the size and position of the tooth roots in the alveolar process. The incision also runs through the mental foramen, indicating its function as the exit point for the inferior alveolar nerve.

Sheet RCIN 919057v (Figure 2) shows two crania (without mandibles) arranged one above the other and aligned to the right. Written notes are present below each cranium. The upper cranium shows the outer bony surface. Lines indicate where the incision on the second, lower drawing is located. The bottom cranium is fenestrated in the area indicated by the lines in the upper drawing, exposing the inner walls of the maxillary sinus and the orbita. To align the crania exactly, they are supported by a cuboid at the mastoid process such that the zygomatic arch runs parallel to the plane of the table. The mere fact that the drawings pay so much attention to the maxillary sinus is already remarkable. In the view where the outer section of the bone is removed, the ostium of the maxillary sinus is depicted as it connects to the nose. It also shows three septa in the region of the maxillary sinus floor. One can guess that the intention was to show how the tips of the maxillary tooth roots shape the floor of the maxillary sinus.

Leonardo also pondered the function of the cavity formed by the maxillary sinus. In the note below the upper cranium in RCIN 919057v (Figure 2), he hypothesized that this cavity contained the sap that nourished the roots of the teeth (O'Malley & Saunders, 2003). While he was wrong about this, the mere idea of asking "Why" is remarkable. It testifies to Leonardo's outstanding wish to question and understand all things. In addition, his ideas demonstrate that he did not classify the teeth as being dead tissue but as living structures.

The third sheet, RCIN 919057r (Figure 3), shows left-lateral profile views of two vertically aligned crania, both with mandibles attached and including some segments of spine. In the upper illustration, the calvaria of the cranium is opened sagittally and transversely: the viscerocranium is left untouched. For the lower illustration, cranium and vertebrae are cut sagittally, exposing the interior walls of the cranium, the frontal sinus, the nose, the mouth, and the vertebrae. In addition, various auxiliary lines are added to measure the cranial proportions. We should not surmise that Leonardo already had the future importance of orthodontics in mind, but he was certainly aware that anatomical planes and connections between structures and joints play an important role in the skeletal system. Some additional details of this drawing deserve mention. The incision on the bottom cranium runs exactly through the maxillary incisive canal, showing the connection between the oral and nasal cavities. Furthermore, the course of the mandibular nerve is visible; it actually leaves the calvaria at the medial cranial fossa through the oval foramen, not through the posterior fossa.

Also depicted is the mandibular foramen. The mental foramen, which allows the nervus, arteria and vena mentalis to emerge from

אנאמוגראפיה חלחח עמך תת ע84: דמקח ע84



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**FIGURE 6** RCIN 919059r Leonardo da Vinci, The cranium, 1489, Pen and ink, 188 × 139 mm, Windsor Castle, Royal Library. Royal Collection Trust/© Her Majesty Queen Elizabeth II 2021. The sheet contains two cranial drawings as well as some handwritten lines. Both drawings show external views and are positioned one atop the other in the sheet's left third. The top drawing shows an incomplete right half of a cranium, visible in quarter profile. Leonardo depicts the orbitae, the nose including its cartilaginous parts, and the right os zygomaticum. His focus is on the vascular system of the viscerocranium and its connection to the interior of the skull, e.g., in the region of the foramen infraorbitale. The bottom drawing shows a calvaria in left lateral view, with an indication of the soft tissues of the nose. The alveolar process of the maxilla only contains three teeth: one incisor, one premolar and one molar. Even though outlines of the teeth are only sketchily indicated, the tooth types can be deduced. At the top of the sheet, Leonardo noted the date when it was created: April 2<sup>nd</sup>, 1489. The text in between the two drawings refers mostly to the representation of the vascular system in the midface

the canalis mandibulae, is indicated in the upper drawing of RCIN 919057 r (Figure 3). Leonardo locates it slightly mesial to the first premolar root. In Figure 1, it is also located approximately at the level of the first premolar. However, comparative studies show that the position of the foramen mentale in the human mandible is highly variable and depending on the age and sex of the individuals concerned as well as their ethnicity (Mohamed et al., 2016). It is most commonly located at the level of or between the first and second premolars, and in exceptional cases elsewhere (Greenstein & Tarnow, 2006; Kqiku et al., 2011). As for Leonardo, one may assume that he placed the foramen mentale on the drawing where he found it in his specimens. In the combination of RCIN 919057r (Figure 3) and RCIN 919058v (Figure 1). Leonardo thus represented almost the entire course of the mandibular nerve. Furthermore, the major palatal canal is also hinted at in the dorsal area of the palate. The palatal bone, on the other hand, is not anatomically distinct from the maxilla.

Beyond the three drawings presented above and their importance for dentistry, two more of Leonardo's cranial illustrations are of interest. Sheet RCIN 919058r (Figure 5) depicts the location and course of the nerves and blood vessels inside the calvaria and the base of the skull, while RCIN 919059r (Figure 6) illustrates the course of various blood vessels on the cranium's exterior, each with some lines of written comment.

The viscerocranium on sheet RCIN 919058r shows the orbita, nose, and maxilla, including its residual dentition, but an exact representation of the teeth seems unimportant (Figure 5). At the bottom of the third ventricle, above the hypophyseal fossa, two lines intersect. This point, near the region later anatomically designated as the nucleus geniculatus lateralis, marks the *senso comune*, where Leonardo assumed that all external sensory impressions came together and were processed (Widmer, 2006). In his opinion, vision was the most significant sensation and he therefore assigned the eye the role of the most important sensory organ (Pevsner, 2002). Leonardo concluded this from his study of the cranial nerves, which he investigated from their origin to the peripheral destinations. In exactly locating the optic nerves in the *senso comune* and the third ventricle, Leonardo da Vinci breaks with medieval tradition (Widmer, 2006). In addition to the nervus opticus, the region of the fossa hypophysialis also contains the n. vestibulocochlearis as well as other sensory nerves, all of which Leonardo depicted (O'Malley & Saunders, 2003). In the accompanying text, Leonardo argues that the uvula, to which he attributes the sense of taste, is also found in that region, and for him this serves as proof that for the location of

the *senso comune* in that area of the brain. Apart from the nerves, the drawing shows a number of intracranial blood vessels, such as the first exact representations of the arteria meningea anterior and media (O'Malley & Saunders, 2003).

The last of the five sheets, RCIN 919059r, focuses on the representation of extracranial and facial blood vessels (Figure 6). According to Leonardo's relatively precise accompanying text, an incomplete right half of a cranium, visible in quarter profile in the upper part of the sheet, depicts the vena maxillaris in the area of the orbita and the zygomatic bone. The near complete cranium in left lateral view in the bottom half of the sheet depicts the vena maxillaris on the opposite side. Here too, the maxillary residual dentition is sketched without much attention to detail.

## 4.2 | The dental anatomy

Three of the drawings, RCIN 919058v, RCIN 919057v, and RCIN 919057r, also show the dentition. Where the teeth are in occlusion, Gerrits judges them to be correctly represented (Gerrits & Veening, 2013), even if they appear to exhibit an edge-to-edge anterior occlusion in the left half of the cranium in sheet RCIN 919058v (Figure 1) and in the upper illustration of RCIN 919057r (Figure 3). From today's perspective, an edge-to-edge bite is considered pathological, even though it constituted the physiological terminal bite position until well after the Middle Ages, dynamically adapted over the lifetime of the individual (Alt et al., 2017). Leonardo thus reproduced the dynamic occlusion in the adult dentition of his time entirely correctly.

An important finding is that the number of teeth (eight per quadrant) is correctly represented. An exception is RCIN 919057r (Figure 3) above. However, one may assume that some teeth were left out intentionally, as the teeth shown are schematic and without the typical characteristics of the respective types. They are also grouped; based on their size and location, it can be assumed that Leonardo drew the two incisors, two premolars, and one molar in the maxilla and mandible, respectively, on purpose. The canine and two molars are absent. Thus, the different types of teeth in the jaw are anatomically recognizable in all three illustrations.

Leonardo da Vinci examined the tooth types in detail and noted the results of his studies in RL 919058r (Figure 1) to the left of the cranium. The illustration shows four teeth, each of which represents one of the tooth types. He also noted the correct number of teeth per jaw. The accompanying text remarks that these were maxillary teeth. His description of the tooth types starts with the molars.

Leonardo explains that they each have three roots, two on the outside and one on the inside of the jaw. In addition, he notes that the third molar does not erupt until the age of 24 (O'Malley & Saunders, 2003). The text assigns an inner and an outer root to the premolars and describes that the canines and incisors each have a single root (O'Malley & Saunders, 2003).

What is striking here is the incongruity between the described two-rooted premolars and the four-rooted premolar clearly discernible in the drawing. Four-rooted premolars are extremely rare; usually the first upper premolars are two-rooted (85%), rarely single-rooted (9%), and very rarely three-rooted (6%). The second upper premolars are most often single-rooted (75%), sometimes two-rooted (24%), and very rarely three-rooted (1%) (Heydecke et al., 2011). It therefore seems very unlikely that Leonardo should have drawn a four-rooted premolar. Gerrits concludes that the depicted tooth may be a permanent molar with severely eroded cusps (Gerrits & Veening, 2013). This would also explain the mesiodistal dimension, which, in the drawing, is comparable to that of the molar and appears oversized for a premolar (Heydecke et al., 2011). Another possibility is that the tooth is a persistent deciduous molar, with Leonardo drawing a given situation he encountered.

With regard to the mandibular teeth, he notes that they resemble those in the maxilla, with the exception of the molars, which have only two roots. Interestingly, in the cranial drawing directly next to the note, a tooth shown as two-rooted in frontal section, presumably a premolar, occludes with a single-rooted tooth, which should actually also be a premolar. Here Leonardo's text and his drawing again contradict each other, since this would mean that the root configurations of the maxillary and mandibular premolars are not identical.

Regarding the function of human teeth, he merely states that the incisors' purpose is to cut. He then digresses to discuss the function of animal teeth, which he considers to differ from that of humans. Also, Leonardo is the first scientist to describe the correct number of teeth and the correct human dental formula, namely that the human dentition comprises four incisors, two canines, four premolars, and six molars per jaw (Gerrits & Veening, 2013).

#### 4.3 | Tooth shape, function, and bite force

Leonardo revisits the importance of the form and function of teeth in 1508 in connection with his research on the digestive system. The sheet numbered RCIN 919041 (Figure 4) shows Leonardo's handwritten thoughts regarding the relationship between form and function of the various types of teeth, which he described as early as 1489. A small diagram consisting of two intersecting straight lines with five points added halfway down the page on the right provides visual clarification. In this short treatise, Leonardo explains his understanding of the nature and position of the teeth in relation to their distance from the center of movement. Point (a), where the two straight lines intersect, represents the center of movement, namely the temporomandibular joint. The other points are teeth at different distances from (a) (modified after O'Malley

& Saunders, 2003). Leonardo concludes that the further away a tooth is from the center of movement, the less masticatory or chewing force it can exert—and, conversely, the closer to the center of movement, the greater the force. The distal molars are located close to the center of movement/temporomandibular joint and thus transmit strong forces. They do not have to penetrate the food; rather, they mash it and therefore exhibit large crowns with blunt cusps. The incisors, located further mesial, have less strength; their shape makes them suitable for cutting and biting food (O'Malley & Saunders, 2003).

### 5 | LEONARDO'S INFLUENCE ON THE STUDY OF HUMAN DENTAL ANATOMY

The cranium drawings impressively demonstrate that Leonardo da Vinci was concerned with anatomy as a whole, but also with smaller anatomical structures of vital importance for today's dentistry. The key role he played for medicine and dentistry was primarily in basic research, which includes anatomy. However, his work was exclusively descriptive and, above all, illustrative in nature, in keeping with his training and his self-image. He never considered himself a physician, which is why, according to current sources, there is hardly any evidence of dental pathology or therapeutic interventions in his work.

This does not mean, however, that Leonardo da Vinci did not see the relevant relationships. When he shows the relation of maxillary roots to the maxillary sinus, ponders the function of the maxillary sinus, differentiates between tooth types by function, determines the correct number of teeth in the dentition, and creates a tooth formula for the jaws, what he does is to provide basic anatomical knowledge for dentistry.

Leonardo apparently wanted to publish his anatomical sketches in the form of a textbook that was supposed to describe the human body throughout life, starting prenatally with sketches of the embryo in the uterus. Unlike previously published reference works on anatomy, the illustrations were to be the decisive didactic element in the planned volume (Herrlinger, 1967). He worked on this project intermittently; in his Milan period, when the cranial studies were created, he was already planning the structure and content of the work (Braunfels-Esche, 1961).

After taking a break from anatomical studies, he resumed this work in 1507–09 (Huard, 1967). The treatise on the relationship between masticatory force and tooth form dates from this period. Leonardo had hoped to complete his work by 1510, but never finished his project; his anatomical sketches were never published (Huard, 1967). But although the work was not completed, Leonardo showed his designs to interested guests; after his death, it was still possible to study his legacy deposited with his heir, Francesco Melzi (Herrlinger, 1967). Although Melzi took care of the estate and wanted to publish the book, he could not realize these plans. Even with the help of two assistants, he was unable to process the vast amount of material (Keele, 1964). After Melzi's death, Leonardo's work reached England via various intermediary stations and was ultimately lost until 1778

(Braunfels-Esche, 1961). Even though Melzi failed to make Leonardo's legacy accessible to the public, it is known that various artists and scientists visited Leonardo while he was still alive, and later Melzi, in order to benefit from Leonardo's findings, including his contemporary Albrecht Dürer, who travelled to Italy in 1505 and whose work exhibits clearly discernible traces of Leonardo's influence (Keele, 1964). Giorgio Vasari, too, recognized the value of the drawings, even though he was not himself an anatomist but an artist and was therefore not really in a position to properly assess the importance of Leonardo's scientific findings (Keele, 1964).

It appears of only minor consequence that Leonardo's findings went unpublished at a time when the printing press had barely been invented. It is quite likely that both Leonardo da Vinci's scientific findings and his method of anatomical representation were handed down orally, being taken up at the universities (Braunfels-Esche, 1961). Anatomical works started appearing more frequently in the first half of the 16th century. It is notable that illustrations dominated as didactic tools, something that is due to Leonardo's influence and shows that his approach had been received. In addition, the work of the surgeon Berengario da Carpi, published shortly after Leonardo's death, contains images of the heart, blood vessels, and extremities that bear great similarity to Leonardo's studies; one may therefore assume that the author had access to Leonardo's designs. One may also assume that Andreas Vesalius had seen Leonardo's sketches. Vesalius is considered the reviver of the science of anatomy with the publication of his highly influential textbook *De humani corporis fabrica* in 1543 (Tubbs et al., 2018). Vesalius's work includes a series of illustrations that bear a striking resemblance to Leonardo's, pointing to his direct exposure to Leonardo's drawings (Braunfels-Esche, 1961).

Leonardo's influence on anatomical publications of the Renaissance has also been documented north of the Alps, of which Hans Gersdorff's *Feldbuch der Wundartzney* in 1617 (Gersdorff, 1970) or the *Spiegel der Artzney* by Lorenz Fries in 1546 (Fries, 1546) bear witness. While these contain original ideas and innovative thought, we nevertheless find clear influences of Leonardo in some illustrations and representations (Braunfels-Esche, 1961). There are further examples to illustrate the acceptance of medical illustrations in anatomy and to show Leonardo da Vinci's lasting influence.

In summary, Leonardo's sketches received more attention and exerted more influence in the artistic than in the scientific realm (Keele, 1964). Nevertheless, there are a number of examples to show that Leonardo da Vinci's successors were well aware of his unpublished discoveries and implemented them in their own work. Keele noted that anatomists would not have stopped quoting Galenus blindly if artists had not begun to question his traditional views of anatomy (Keele, 1964).

## 6 | LEONARDO DA VINCI AND DENTISTRY—A FINAL NOTE

Leonardo da Vinci's work includes many discoveries that were far ahead of his time, and this is also true of the field of dentistry. His revolutionary approach enabled him to depict structures such as the

maxillary sinus long before they were "discovered" later. While the science of anatomy was still in its infancy during the Renaissance period, he already succeeded in grouping the teeth and reciting the correct dental formula. He also gave some thought to nutritional aspects of the dentition, which implies a completely novel perception of teeth as organic structures rather than dead matter. Leonardo meticulously studied the nervous and vascular systems of the skull and located the *senso comune* (his "seat of the soul"), where all external sensations arrive and are processed, in the third ventricle.

Leonardo da Vinci also recognized the connection between the form, function, and strength of teeth. Had Leonardo da Vinci's anatomy textbook been published as planned, his importance for dentistry would quite likely not have been overlooked. And even if Leonardo's thoughts on how teeth were provided with nutrients were incorrect in the light of what we know today, they would have given his readers food for thought and supported the advancement of research.

The greatest innovation that can be traced back to Leonardo, however, one that is also eminently relevant to dentistry, is the introduction of drawings as a didactic tool in anatomy. Perhaps this is the fate of the universal genius: his estate was so extensive that his and the following generation could not cope with the amount of information he had compiled. This is one reason why Leonardo da Vinci is mainly known for his paintings today, even though they provide only a tiny window of insight into his entire oeuvre.

## ACKNOWLEDGMENTS

The authors thank the Royal Collection Trust, London, especially Karen Lawson, Picture Library Supervisor, for their kind and generous permission to reproduce six images by Leonardo da Vinci. The authors also thank Per N. Döhler for translation of the manuscript and Sandra L. Pichler for her constructive comments and language review of the final version of the text.

## CONFLICT OF INTEREST

No conflict of interest has been declared by the authors.

## AUTHOR CONTRIBUTIONS

Both authors contributed to the conceptualization and design of the research, to the interpretation of the drawings of Leonardo da Vinci, and to the writing and correction of the manuscript.

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**How to cite this article:** Schuez, I. & Alt, K.W. (2022)

Leonardo da Vinci and dental anatomy. *Journal of Anatomy*, 240, 183–196. <https://doi.org/10.1111/joa.13561>